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SOME OBSERVATIONS ON THE CAUSES, BEHAVIOR, AND CONTROL OF FIRES IN STEEP-PITCH ANTHRACITE MINES

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BY

G. E. MCELROY

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SOME OBSERVATIONS ON THE CAUSES, BEHAVIOR, AND CONTROL OF FIRES IN STEEP-PITCH ANTHRACITE MINES[1]

By G. E. McElroy[2]

INTRODUCTION

As one phase of a general program of anthracite mine-fire research initiated by the Bureau of Mines in September 1935, a study of the records of past fires was considered a necessary approach to a proper understanding of present and future fires because only limited information could be obtained directly from existing active fires on account of their inaccessibility. Through the courtesy of interested operators, all available records of fires that had occurred in a large group of steep-pitch anthracite mines in the Western Middle and Southern fields of the Pennsylvania anthracite district were examined and analyzed for data on the causes, costs, behavior, and control of fires, and this report is primarily a discussion of these factors based on a close study of these particular records.

Mining Conditions

The records pertain to a group of mines that have contributed about 12 percent of the total Pennsylvania anthracite production and constitute a large proportion of, and well represent, steep-pitch operations in this district. Throughout the area represented, the coal occurs as a series of up to 20 parallel seams in folded slate and sandstone strata and almost entirely on pitches of 40° to 80°, with vein thicknesses of 5 to 60 feet. Practically all are old mines with histories dating back to 1850, or thereabouts, and present operations are either under or adjacent to mined-out areas extending to surface or to the saddles of anticlines. All operations are at relatively shallow depths, that is, within 1,000 feet, vertically, of the surface. Mining methods are largely a heritage of the past and embrace typical breast and pillar operations with practically no mechanized mining and with the coal shot "off the solid." Most of the mines are rated as gassy and are operated now on a closed-light basis. Permissible explosives are now used entirely for breaking coal, and dynamites for rock work and chute-starting blasting.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7025."

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Records

Fires occur rather frequently in these mines. In fact, it has been unofficially estimated that there have been, on an average, two fires per day underground in the group considered. However, practically all have been of negligible importance - usually a shot igniting a few small gas feeders at a working face - and have been extinguished easily and quickly by the men at hand. These insignificant fires, as well as many of those of somewhat more consequence, rarely become a matter of permanent record. It therefore seemed desirable to distinguish between such minor fires and those of a more serious nature. Fires put out during the shift in which they were discovered and which had an estimated total cost of less than $150 were therefore designated as minor fires and those of greater duration and cost major fires. On this basis, there were records of 103 major fires and 74 minor fires, and references, without any substantiating data as to time or place, to possibly half a dozen more that occurred mainly during the period 1850 to 1870.

Since many of the records contained no statements as to causes or costs and were otherwise incomplete, the records for each fire were finally studied in conferences with various mine officials, to determine the most probable cause and to estimate the probable direct cost of fighting the fire, as well as to obtain, as far as possible in a limited time, other data pertinent to each fire.

CAUSES AND COSTS OF FIRES

The fact that causes were assigned, rather than definitely known, for almost half of the major fires considered in this record, and that direct costs for about 80 percent of them, were estimated rather than taken from actual records, would appear to make any compilation valueless. Although this might have been the case had the author's judgment alone been involved, the assignments and estimates were made in most cases by officials who were either familiar with the particular fire or were thoroughly familiar with underground conditions, fire fighting, and estimating the cost of fighting fires, so that, although the individual data undoubtedly are inaccurate in many respects, the total picture they yield is believed to be substantially accurate as to the relative causes of fires and but a slight understatement of the actual cost of fighting them.

Major Fires

Data for 103 major fires are tabulated, by causes and costs for 10-year periods, in table 1, in which recurrences are treated as separate fires and all costs are charged to the ten-year period in which they were incurred. Such direct totals give a rather misleading idea of the relative importance of causes and the division of responsibility for costs by periods, so a revised tabulation is presented as table 2, in which only the original fires are considered and in which all costs, including those of the 22 recurrences, are charged to the periods in which the fires originated. On this basis, there were 81 separate fires. Of these, the origins of 42 are definitely

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known, and the most probable origin of 32 others can be surmised from the records and surrounding circumstances. In the case of the remaining seven, no cause can be assigned, owing to lack of data.

Allowing for a few unrecorded major fires in the early part of the period covered by this record, the number of fires per 10-year period shows a decided jump for the period from 1900 to 1909, an increase to maximum from 1910 to 1919, and but a slight decrease (accompanying a rapid decrease in production) since then.

Minor Fires

Similar data for 71 small fires for which some records were found have been tabulated in table 3. Assuming that these 71 fires are representative of the small fires that occurred during the time mentioned, a significant decrease in number is indicated and fair agreement as to relative causes with the basic tabulation of table 2.

Causes of Fires

The tabulated data of tables 1 and 2 show that the three predominating causes of fires have been explosives, open lights, and open fires, with smoking a low fourth and electricity an almost negligible fifth; they also show that recurrences (which may be considered as fires caused by ineffective fire-fighting methods) rank first as to cost and second as to number.

Gas Ignitions and Explosions

Table 2 indicates that, with respect to major fires, gas ignitions and explosions have been the direct cause of six charged to open lights, ten charged to use of explosives, and one charged to smoking. At first glance, the proportion of fires involving gas ignitions - 17 of 81 - might be taken to indicate the effect of poor ventilation as an indirect cause of fires; yet few of the records would bear out such a supposition, as the majority appear to have been caused either by abnormal gas conditions, due to outbursts, rushes of coal, or falls, or by the carelessness of the miners in not testing for gas or in wandering into returns and abandoned openings with open lights.

TABLE 1. - Causes and costs of 103 major mine fires, with recurrences considered as separate fires and costs charged as incurred

Cause of fire	1850-59		1860-69		1870-79		1880-89		1890-99		1900-09	
	No.	Cost	No.	Cost	No.	Cost	No.	Cost	No.	Cost	No.	Cost
EXPLOSIVES:												
Direct -known											1	$ 1,000
-probable											2	76,000
Via gas-known											2	8,000
-probable												
Total											5	85,000
RECURRENCES:												
-known							1	$24,000	3	$32,000	1	1,000
-probable							1	20,000	1	1,000		
Total							2	40,000	4	33,000	1	1,000
OPEN LIGHTS:												
Direct -known											1	75,000
-probable							1	50,000			4	3,750
Via gas-known					1	$50,000	1	5,000	3	30,500		
-probable												
Total					1	50,000	2	55,000	3	30,500	5	78,750
OPEN FIRES:												
Direct -known	1	$10,000	2	$102,000								
-probable	1	5,000					1	500				
Total	2	15,000	2	102,000			1	500				
SMOKING:												
Direct -known												
(1 via gas)-probable											1	30,000
Total											1	30,000
ELECTRICITY:												
Direct -known												
UNKNOWN:												
No records					1	20,000	2	22,000	1	500	2	10,250
TOTAL	2	15,000	2	102,000	2	70,000	7	117,500	8	64,000	14	205,000

TABLE 1. - Causes and costs of 103 major mine fires, with recurrences considered as separate fires and costs charged as incurred - Continued.

Cause of fire	1910-19		1920-29		1930-36		Totals			
	No.	Cost	No.	Cost	No.	Cost	No.	Percent of total	Cost	Percent of total
EXPLOSIVES:										
Direct -known	4	$ 2,200	3	$ 4,350	3	$73,685	11	10.7	$ 81,235	3.9
-probable	2	5,755	3	18,000	2	76,000	9	8.7	175,755	8.3
Via gas-known	2	3,000	1	250	1	5,000	6	5.8	16,250	.8
-probable	2	450	2	51,000			4	3.9	51,450	2.4
Total	10	11,405	9	73,600	6	154,685	30	29.1	324,690	15.4
RECURRENCES:										
-known	5	163,000	1	50,000	5	156,810	16	15.6	422,810	20.1
-probable			3	103,500	1	60,000	6	5.8	184,500	8.8
Total	5	163,000	4	153,500	6	216,810	22	21.4	607,310	28.9
OPEN LIGHTS:										
Direct -known	2	3,300	1	20,000			4	3.9	102,800	4.9
-probable	2	75,500	1	1,000			8	7.8	130,250	6.2
Via gas-known	1	450					6	5.8	81,450	3.9
-probable			1	60,000		73,900	1	1.0	133,900	6.3
Total	5	79,250	3	81,000		73,900	19	18.5	448,400	21.3
OPEN FIRES:										
Direct -known	1	560	1	400	7	19,820	12	11.6	132,780	6.3
-probable	1	280,000	2	9,450	1	148,355	6	5.8	443,305	21.1
Total	2	280,560	3	9,850	8	168,175	18	17.4	576,085	27.4
SMOKING:										
Direct -known			1	50,000			1	1.0	50,000	2.4
(1 via gas)-probable	2	3,500	1	1,000			4	3.9	34,500	1.6
Total	2	3,500	2	51,000			5	4.9	84,500	4.0
ELECTRICITY:										
Direct -known			1	500	1	500	2	1.9	1,000	
UNKNOWN:										
No records	1	10,000					7	6.8	62,750	3.0
TOTAL	25	547,715	22	369,450	21	614,070	103	100.0	2,104,735	100.0

TABLE 2. - Causes and costs of 81 original major mine fires, with all costs charged to original cause and period of origin

	1850-59		1860-69		1870-79		1880-89		1890-99		1900-09	
Cause of fire	No.	Cost	No.	Cost	No.	Cost	No.	Cost	No.	Cost	No.	Cost
EXPLOSIVES:												
Direct -known											1	$ 1,000
-probable											2	204,500
Via gas-known											2	83,000
-probable												
Total											5	288,500
OPEN LIGHTS:												
Direct -known											1	75,000
-probable							1	$71,000			4	3,750
Via gas-known					1	$50,000	1	5,000	3	$30,500		
-probable												
Total					1	50,000	2	76,000	3	30,500	5	78,750
OPEN FIRES:												
Direct -known	1	$32,000	2	$152,000								
-probable	1	5,000					1	82,100				
Total	2	37,000	2	152,000			1	82,100				
SMOKING:												
Direct -known												
(1 via gas)-probable											1	30,000
Total											1	30,000
ELECTRICITY:												
Direct -known												
UNKNOWN:												
No records					1	20,000	2	44,000	1	1,500	2	10,250
TOTAL	2	37,000	2	152,000	2	70,000	5	202,100	4	32,000	13	407,500

TABLE 2. - Causes and costs of 81 original major mine fires, with all costs charged to original cause and period of origin - Continued.

Cause of fire	1910-19		1920-29		1930-36		Total			
	No.	Cost	No.	Cost	No.	Cost	No.	Percent of total	Cost	Percent of total
EXPLOSIVES:										
Direct -known	4	$ 2,200	3	$ 4,350	3	$73,685	11	13.6	$ 81,235	3.9
-probable	2	5,755	3	18,000	2	122,210	9	11.1	346,965	16.5
Via gas-known	2	6,500	1	250	1	5,000	6	7.4	94,750	4.5
-probable	2	450	2	51,000			4	4.9	51,450	2.4
Total	10	14,905	9	73,600	6	200,895	30	37.0	574,400	27.3
OPEN LIGHTS:										
Direct -known	2	3,300	1	20,000			4	4.9	102,800	4.9
-probable	2	235,500	1	1,000			8	9.9	311,250	14.8
Via gas-known	1	450					6	7.4	81,450	3.9
-probable			1	133,900			1	1.2	133,900	6.3
Total	5	239,250	3	154,900			19	23.5	629,400	29.9
OPEN FIRES:										
Direct -known	1	560	1	400	7	19,820	12	14.8	204,780	9.7
-probable	1	410,000	2	3,450	1	24,355	6	7.4	524,905	24.9
Total	2	410,560	3	3,850	8	44,175	18	22.2	729,685	34.7
SMOKING:										
Direct -known			1	50,000			1	1.2	50,000	2.4
(1 via gas)-probable	2	3,500	1	1,000			4	4.9	34,500	1.6
Total	2	3,500	2	51,000			5	6.1	84,500	4.0
ELECTRICITY:										
Direct -known			1	500	1	500	2	2.5	1,000	-
UNKNOWN:										
No records	1	10,000					7	8.6	85,750	4.1
TOTAL	20	678,215	18	283,850	15	242,070	81	100.0	2,104,735	100.0

TABLE 3. - Causes and costs of 71 recent minor[1] mine fires

Cause of fire	1910-19		1920-29		1930-36		Total			
	No.	Cost	No.	Cost	No.	Cost	No.	Percent of total	Cost	Percent of total
EXPLOSIVES:										
Direct -known	3	$100	3	$170			6	8.5	$270	12.7
-probable	1	0	1	0			2	2.8	0	0
Via gas-known	6	205	4	150	2	$125	12	16.9	480	22.5
Total	10	305	8	320	2	125	20	28.2	750	35.2
OPEN LIGHTS:										
Direct -known	6	70	5	20			11	15.5	90	4.2
-probable	5	200	1	25			6	8.5	225	10.6
Via gas-known	3	0	1	100			4	5.6	100	4.7
Total	14	270	7	245			21	29.6	415	19.5
OPEN FIRES:										
Direct -known	3	125	2	45	5	240	10	14.1	410	19.2
-probable			3	100	1	25	4	5.6	125	5.9
Total	3	125	5	145	6	265	14	19.7	535	25.1
SMOKING:										
Direct -probable	4	150	2	0	1	130	7	9.9	280	13.2
ELECTRICITY:										
Direct -known	2	0	1	75	5	75	8	11.3	150	7.0
UNKNOWN:										
No records			1	0			1	1.4	0	0
TOTAL	33	850	24	685	14	595	71	100.0	2,130	100.0

[1] Fires lasting less than one shift or costing less than $150.

Use of Explosives

From about 1900 to date, the chief cause of all fires, and particularly of the more serious ones, has been the use of explosives. About a third were due to gas ignitions and explosions caused by blasting, which either set fire to timber or to gas feeders buried in broken coal. The other two-thirds were direct occurrences without the known intervention of gas and were attributed largely to burning explosives. In first mining operations such fires have not been particularly serious, as the results of shots are under constant observation. In pillar mining operations, the free-running nature of the coal in many places is considered to require large-scale blasting of pillar sections as a matter of safety and under such conditions that the result of a blast cannot be inspected. As the ventilation current virtually always travels away from the men and up through the broken coal and rock, a fire usually is not detected until burning material is drawn out of the chute, which may occur in a day, a week, or a month. Under such conditions, the chances are good that a fire may make considerable headway in an area where it is a difficult matter to extinguish it, and many very serious fires have thus resulted.

Although most fires of this type have been attributed to burning explosives, it is probable that some were started by local explosions of the gaseous products of explosives[3] where large blasts were fired in rapid succession in certain large-scale pillar mining operations. Experiments were made in a few places in recent years in the simultaneous blasting of whole pillars between lifts, using several hundred pounds of explosives in up to 100 holes fired in groups with delay igniters. One such large blast is thought to have been the cause of one of the more recent serious fires, which cost $70,000 to extinguish it and an additional indirect cost at least as large; and these experiments have been discontinued.

Considering the extent of the blasting operations conducted in this group of mines, it is not surprising that the extensive use of explosives in combustible materials should be a major cause of fires. Permissibles are now used exclusively in coal and dynamites in rock, and all are fired electrically. About 4,000,000 shots are fired yearly, in which approximately 4,000,000 pounds of explosives are used - about 60 percent dynamite and 40 percent permissibles. An extensive program of driving rock gangways accounts for the large proportion of dynamites, which are also used for most chute-starting blasting, for which the annual requirements are about 650,000 pounds of explosives.

Changes in general practices have been made from time to time which have eliminated known causes of fires, but explosives are still a major hazard and one that warrants intensive investigation. Multiple-shot blasting of pillar sections and open-shot chute blasting appear to be the practices requiring modification for greater safety as respects fire hazards.

Recurrences of Old Fires

Table 1 shows 22 fires listed as recurrences of old fires, 16 of which were known to be such and 6 of which probably were. Many of those classed as known were not so designated in the records, but the connection to an earlier fire was obvious from a study of maps and the records. Of the six classed as probable, the connection was not so obvious but could be inferred easily from relative positions and surrounding circumstances, although it was not possible to say just how the connection was established without earlier recognition. It is also probable that some large fires attributed in this analysis to other causes may actually have been recurrences, even though certain surrounding circumstances appeared to prove the contrary.

In certain cases, fires were drawn down onto successive levels, or lifts, as many as three or four times, but since many lifts lasted 20 years and more, the actual fires were separated by such long intervals as to engage an entirely different personnel, and in many cases, they were considered new fires. While recurrences have been one of the major difficulties in steep-pitch workings, an increasingly better understanding of the behavior and control of fires should do much to reduce their number in the future.

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[3] Jones, G. W., Inflammability of Mixed Gases: Tech. Paper 450, Bureau of Mines, 1929, p. 34.

Open Lights

Although "open lights" appears in tables 1 and 2 as a major cause of fires, this cause has been eliminated in this group of mines through the introduction of electric cap lamps, which are now used everywhere except in a few water-level tunnel workings. No fires from this cause were recorded for the period 1930 to 1936. Virtually all open lights had been removed from gassy sections by 1915, but the use of mixed lights continued in non-gassy operations until about 1930.

Six of the 19 fires ascribed to open lights resulted from gas ignitions that were caused in various ways but more often were due to gas outbursts (in one case such an outburst forced the flame through a safety lamp gauze and ignited the gas), rushes of coal, and falls of rock. Fires caused directly by open lights were due in six cases to timbermen working in a dry place and leaving the place without knowing that one of their lamps had started a fire in the timber. An occasional fire in pump room or stable was noted in the early records; but these were very few, considering the steam-pipe-dried timbering of pump rooms and the vast quantities of easily combustible hay transported and stored underground at that time.

Open Fires

While "open fires" appears in table 2 as the third of the major causes of fires, on the basis of both number and cost, the number is due largely to recent small fires and the cost to two old fires, still active, on which a tremendous amount of money has been expended and which possibly may have been due to other causes. While the danger from open surface fires is real indeed, it is by no means as acute as the statistics might imply. Open breaches cover many square miles of surface, partly adjacent to mining communities and partly on isolated hillsides covered with second-growth timber and brush. Brush fires are common; boys and tramps rendezvous in the breaches, and the breaches make ideal places for dumping ashes and rubbish. Certain areas might be fenced in and others leveled or covered, but these measures are impracticable as general solutions, and the only economical methods of guarding against fires would seem to be constant patrol of the areas liable to brush fires, and making certain that fires are extinguished when found. Three major and two minor fires that occurred from 1930 to 1936 were attributed to "bootleggers"; the number of such fires will probably increase rather than decrease while this activity endures.

Although four major fires are considered to have been caused by three forest fires, there is no definite evidence except in the case of one. Brush fires, caused almost entirely by railroad locomotives, have always been a grave hazard which apparently was overcome to a considerable extent by an intensive campaign begun late in 1920 and continued through 1923 and possibly later.

Smoking Underground

Although smoking underground has always been prohibited, enforcement has not always been strict in relatively nongassy sections of mines, and there are always miners who will sneak a smoke whenever possible and discard it recklessly on the approach of an official. Definite proof that a fire was thus caused is usually lacking because the evidence is consumed by the fire. Only one major fire is known definitely to have had such an origin, while for four major and seven minor fires it is assigned as the most probable cause. In one suspected case, in 1913, the seven men working in the immediate vicinity of a fire in a closed-light section were searched immediately, and cigarette smoking materials were found on all seven, who were forthwith discharged. But one small fire was attributed to this cause in the 1930-36 period.

Use of Electricity

The small number of fires of electrical origin and the minor nature of most of them were rather surprising features of these records. One major fire was due to an overloaded 350-horsepower hoist motor but there was no damage except to the motor. The other major fire recorded was due to a fall at a turnout, and the expense was practically that required for cleaning up the fall. Two of the eight minor fires were also due to falls, and three others were merely short-circuits in trolley hangars. The increasing use of electricity underground, starting about 1910, is not reflected in the mine-fire record in the case of this large group of mines.

Spontaneous Ignition

It was thought close examination of records would reveal indications, that might be followed up in the field, of "mysterious" fires caused by spontaneous ignition of coal, adjacent strata, or materials associated with the mining of anthracite. It may be said that nothing in the records indicates that either anthracite or the adjacent strata have fired spontaneously, even though certain areas do heat to an abnormal extent. While laboratory work on this phase of the problem has not been completed, no coal seams or strata examined 4/ have ignition temperatures at all close to those of coals known to fire spontaneously.

Common sources of spontaneous ignition, such as oily waste in engine, pump and fan houses, and rubbish dumped into surface breaches, were the probable causes of one minor (breach) and two major (fan-house) fires listed as due to open fires and possibly of some of the fires attributed to open lights. But there is nothing in the record to indicate that the few materials often thrown into the gob in such mines have resulted in fires.

4/ Scott, G. S., and Jones, G. W., Oxidation of Anthracite: Ind. and Eng. Chem., vol. 29, Jan. 1937, pp. 106-8.
Scott, G. S., and Jones, G. W., Significance of Low-Temperature Oxidation Products in Anthracite Mine Fire Studies: Ind. and Eng. Chem., vol. 29, July 1937, pp. 822-6.

Heating in Mines

As has been said, certain areas in these mines do heat to an abnormal extent, but only where the ventilation is sluggish or absent. Maximum air temperatures in such areas range from 90° to 100° F., indicating that the total production of heat is not large. It is very possible that the cause is the same as that for locally-heated areas in a number of metal mines - pyrite disseminated through adjacent strata in such fine-grained form as to be revealed only by microscopic examination and generating perceptible heat only in crushed areas. A study to determine the cause and conditions of this heating would be desirable.

Friction

No evidence was found in the records of these fires of either gas explosions or fires caused by the effect of friction of rock on rock or sheet iron, although this is known to be a source of ignition of gas in bituminous coal mines. Instances were cited by mine officials of intensive-appearing sparks created by large roof falls in steep-pitch pillar-mining operations, but none were cited of such sparks causing gas or coal ignitions. The records include a number of mysterious explosions following which fires were found, but in all cases it seemed more logical to ascribe the explosion and fire to some initial cause other than friction.

If friction were a factor, a logical place to look for such fires would be where pillar-mining operations on steep pitches started to retreat from a barrier pillar, assuming that the main roof break might not occur until a considerable amount of open space had been formed, so that a large slab falling from the roof might attain considerable velocity sliding down 200 to 300 feet on the bottom slate. Special inquiries were made regarding three fires that occurred under such general conditions, but the information was that in each case the rock followed closely the drawing of the coal and no large open spaces occurred; more probable causes were therefore assigned to these fires.

Costs of Fires

Table 1 shows that recurrences have been responsible for almost a third of the total direct cost of fires. Since the cost of such fires, as well as much of the cost of fighting other fires, particularly four that are still active and may easily entail additional costs of as much as a million dollars, whether extinguished or allowed to burn, can be attributed to ineffective fire-fighting methods, it seems entirely probable that more than half of the total cost of fires in this group of mines can be charged to improper procedure. This condition has been gradually remedying itself by the trial-and-error method, but it still provides an extensive field for study and research.

Direct Costs

Although the tabulated direct costs given must be considered as rough approximations, it is a well-known law of mathematics that where random errors only are involved the accuracy of the total of a large number of items is much greater than that of the individual items. The total direct cost shown, $2,105,000, is probably somewhat low, owing to items and fires not included in the records, and it is possible that a more correct figure would be somewhat less than $2,500,000.

Much of this expense was incurred at low wage and price levels; in terms of present-day wage scales and material costs, the foregoing amount represents an equivalent expenditure now of approximately $4,000,000.

The fact that the costs of minor fires are not included is not significant, as their cost is negligible, as shown by table 3, where 71 minor fires have an aggregate estimated cost of but $2,130. Sufficient data are not at hand to attempt any distribution of costs. A few records, however, indicate that the general relation has been approximately 80 percent for labor and 20 percent for materials.

Indirect and Total Costs

Although the direct cost of fighting mine fires in these mines has been large, even considering the magnitude of the operations, the indirect cost must be even larger and the total cost an immense sum. It is difficult to form any estimate from the records as to what these indirect costs might include, nor is it possible to make any close estimates. The records abound with instances of important producing collieries, or large sections of them, being shut down completely for months at a time while fires were being fought, of large blocks of reserves rendered inaccessible for years and decades, and of large reserves and even collieries abandoned on account of mine fires. Occasional estimates that are to be found in the records give some information on these indirect costs, from which it would appear that if they could be properly adjudged it would be found that they average between one and two times the direct cost; and the indications are that in present day values mine fires have cost this group of mines at least $10,000,000, equivalent to about 2 cents per ton of coal produced. And, on the same approximate basis, an estimate can be made that mine fires in the Pennsylvania anthracite district have cost the operators not less than $50,000,000, equivalent to about 1-1/4 cents per ton of coal produced.

Casualties Due to Fires

This group of records shows that gas explosions that caused fires resulted in at least 15 fatalities and 15 cases of serious injury, and that the actual fires accounted for at least 18 fatalities and 24 cases of serious injury. Explosions and mine-fire gases due to unsuspected recurrences were responsible for at least 4 killed or suffocated, 10 seriously injured, and many overcome; at least 6 men were suffocated while trying to escape from fire gases, and many were overcome but rescued; 7 men were suffocated by fire gases in a mine adjoining one on fire; and a foreman was killed and 5 of his crew seriously burned by an explosion when they entered a fire area to salvage equipment, contrary to orders. Undoubtedly, there were other casualties due to mine fires that were not noted in the existing incomplete records, but it is evident that the number has been small, considering the character and extent of the hazard.

Regardless of the fact that fighting mine fires in steep-pitch gassy anthracite workings is about as difficult and dangerous a job as can be imagined, the record of men seriously injured fighting mine fires is surprisingly low. During actual fire-fighting operations, four men were badly burned by steam when the water was turned on by mistake, two were badly burned by a gas explosion, and three were seriously affected by being overcome by fire gases. The hazard of such work is evidenced by the number of men slightly injured or overcome by fire gases. The facts on these cases are, for the most part, mentioned only incidentally in the records examined, so that, while a total of only about 50 could be gleaned from the records themselves, it is possible that the actual number was well over 100.

Many of the cases of men being overcome while fighting mine fires occurred before oxygen breathing apparatus and gas mask apparatus came into general use, but many have occurred since such devices were made available, as their use has apparently been quite limited in these fields.

BEHAVIOR OF MINE FIRES

Most fires in accessible workings, as in the broken coal in a breast, are attacked directly and extinguished, and little needs to be said about them. The serious fires are those that occur in caved and virtually inaccessible areas, where direct attack often fails to extinguish the fire, whether the fact is realized at the time or not. The records examined are full of instances of fires that were considered to be extinguished but that recurred after intervals of weeks, months, or years, even under circumstances where maximum effort had been made to assure that the fire was completely extinguished. In many cases, affected areas were sealed off, and lack of indications at remote points was taken as evidence that the fires had been extinguished. The very fact that often the only available evidence of the progress of fires is what can be determined by deduction from observations made at remote points, makes it difficult to determine with absolute certainty whether or not such fires have been extinguished.

Evidently, a considerable series of physical and chemical phenomena are involved, some of which are generally understood and some of which are not. While laboratory research may be expected to develop unsuspected leads as to factors involved in recurrences and methods of analysing the results of remote observations, and detailed investigations of fire areas, where feasible, may offer proof of things now only surmised, it is felt that known physical and chemical phenomena can account for most of the known recurrences.

Natural Ventilation in Sealed Fire Areas

The most important factor in the propagation of fires in partly sealed areas on steep pitches is natural ventilation, or the circulation of air currents due to differences of temperature and elevation. Circulation occurs even if the seals are perfect and is then an important factor in dissipating the heat generated by the fire.

In the case of these fires the seals have not been perfect, as practically all of the costly and dangerous recurrences have been in second-mined and caved areas extending to the surface or to the saddles of anticlines. Even though caved ground and surface soil appear to be compact, they are essentially porous as far as allowing air to pass through is concerned, and large openings exist in the broken strata over anticlines. All fires in areas breached to the surface or under anticlines, therefore, have what amounts to an open top. Through such an open top a circulation of air to a fire at any depth can be affected by natural ventilation currents set up by the heat of the burning material and variations in gas densities. The air flow may be circulation to and from the surface or adjacent unsealed areas or recirculation through openings in the sealed area, or both, depending on the relations of existing openings.

Not only is a flow of air set up throughout sealed areas, but it is also possible for natural draft pressures generated by a fire above active workings to cause air from exhaust-fan circulations to be upcast to the surface through the fire area, instead of air from the fire being drawn into the exhaust ventilation system. Whether or not such action occurs depends entirely on the relative pressures of the fire area natural draft and the fan pressure. This fact alone, it is thought, has had much to do with the fact that recurrences took place where they were least expected, as it has been commonly supposed that an exhaust system provides an unfailing check on the presence of a fire in adjacent caved areas.

These natural circulations also have a great deal to do with the directions in which fires propagate. Where the air supply is small, extinctive gases generated by the fire accumulate just up the pitch above it and hinder propagation up the pitch. The same gases also limit lateral propagation to some extent, but the bottom of the fire area gets the purest air and burns the strongest; hence, in caved areas the fastest rate of extension is usually down the pitch. However, where the supply of air is abundant, due to the comparative openness of the caved material, the ascending fire gases may be mixed with sufficient air to burn readily and the fire will spread rapidly both up the pitch and laterally.

The fineness of the broken material and the relative amount of open space in it are therefore important elements in determining the behavior of the fire in caved areas. Near the surface and in thick seams or closely spaced seams, the caved ground is comparatively open and fires spread rapidly up the pitch and laterally and at the same time fairly rapidly down the pitch. At greater depths and in thin seams, the general mode of extension is slowly down the pitch and laterally. In some cases the ground is so compact that the fire apparently barely exists after the ground has settled following pillar mining and only becomes active when the ground is again disturbed, as by the "run" of a breast in first mining or the mining of pillars in the lift below.

Long Dormant Fires

It is difficult to explain how fires could exist for as long as 15 to 25 years with no surface indications and yet become ragingly active in a very short time after the ground is disturbed by pillar mining on the seam below a supposedly extinguished fire. The two main factors thought to be involved are the low heat conductivities of the materials involved and the "conditioning" of the materials by long-continued heating. Anthracite coal, either solid or finely divided, has particularly low conductivity values - about one-tenth those of igneous rocks. The adjacent materials, usually slates, also have quite low values.

Once a fire has originated in pillar-mined territory on a steep pitch, the initial fire-fighting methods of sealing, with or without slushing and covering of breaches, materially reduce the supply of air and limit both the intensity and size of the fire. With tight seals and rather open ground, a circulation of air of sufficient intensity might be set up that would convey heat away from the fire sufficiently quickly to extinguish it in time. Usually, the fires are in "tight" ground and the air currents are so sluggish that heat transfer is mainly by conduction and at too low a rate to reduce the temperature of the burning mass below the point of re-ignition; and the fire continues to burn in local areas at a rate depending on the combustible content and physical nature of the caved mass and the oxygen content of the air supply. Hot gases arising from such dormant fire areas may pass so slowly to the surface that their temperature is reduced to that of the surface soil, where they emerge in such diffused quantities as to be undetected. The fact that snow in breaches over suspected fire areas remains unmelted is therefore no indication that the fire is out - only that it is practically dormant, that is, burning in small isolated areas where conditions are favorable or possibly merely oxidizing at a high rate and generating sufficient heat to maintain a temperature that will permit re-ignition whenever sufficient air can reach it.

"Conditioning" of Materials in Fire Areas

The rapidity with which certain recurrences of fires have gained headway and with which sealed fires have become ragingly active after seals were opened is attributable, in the author's mind, to a "conditioning" of the materials in the fire area by long-continued heating at relatively low temperatures. Regardless of what the action is, it can be demonstrated easily in a house-heating furnace burning anthracite. If the drafts are shut off after a good fire has been covered with a thick layer of fine coal and allowed to remain so overnight, there will be a roaring fire the next morning within a few minutes after the drafts are opened. Yet the same intensity could not have been obtained in less than an hour after the fire was covered, regardless of the method of firing or of manipulating the drafts.

Possibly nothing more is involved than driving off some of the water in the coal, its partial heating, and possibly a moderate amount of oxygen absorption, but the author is inclined to believe that something more is involved, possibly something to do with the power of anthracite to absorb gases.

A somewhat similar "conditioning" of timber in contact with moderate temperatures such as generated by steam pipes in pump rooms and columnways, whereby heavy timbers are brought to the point where they are easily ignited by an open light, is recognized generally throughout the anthracite district as the result of a number of disastrous fires primarily due to this effect. But the "conditioning" of materials in fire areas, particularly fine coal slushed into fire areas to extinguish fires by preventing access of air to them, does not seem to have been recognized.

Many fires that were supposedly extinguished by slushing have recurred when the area was disturbed. In these cases it is considered that the slushing probably extinguished the fire over large areas, but that, locally, burning masses were insulated by consolidated fines through which a sufficient supply of air filtered to keep the fire burning at low intensity over a long period, measured in years, during which the surrounding material became "conditioned", so that when later workings below the fire area caused movement and cracks in the consolidated fines that permitted a proper air supply, the prepared material burned freely and generated an intense fire in a very short time, measured in hours or days.

The probability that such a train of circumstances will occur is therefore a strong argument for discontinuing the use of coal fines for slushing fire areas, a method which, until recent years, has been extremely popular.

Role of Hydrogen in Propagating Fires

A characteristic of the combustion of anthracite coal is the amount of hydrogen gas given off by high-temperature distillation, in which respect it differs from coals of lower rank. Above about 1,100° F. (red heat), approximately three-quarters of the gas produced is hydrogen. While this is a subject pertaining particularly to laboratory investigations[5] now in progress, it seems pertinent to discuss its relation to fires at this point.

As hydrogen is an exceedingly light gas (density about one-fifteenth that of air) with wide explosive limits (4 to 74 percent in air), the fact that large quantities may be generated by burning anthracite must be an important factor in the propagation of fires and may easily be the most important factor in explaining their "mysteriousness." By its very nature, hydrogen would accumulate in all openings above an active fire area, and it is easy to imagine a chain of events by which the repeated accumulation, exploding or burning of hydrogen-air mixtures could communicate fires long distances through openings in the strata, particularly along saddles of anticlines and along barrier pillars, without leaving much evidence behind of the path of communication.

This is the most plausible explanation, and that accepted by company officials, of the method by which the famous Summit Hill fire of the Lehigh

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[5] Scott, G. S., and Jones, G. W., Composition and Inflammability of Gaseous Distillation Products from Heated Anthracite: Report of Investigations 3378, Bureau of Mines, 1938, 6 pp.

Coal & Navigation Co. crossed the half-million-dollar concrete and clay barrier erected to stop it. It was also very possibly the mode of origin of a number of the major fires in the group of mines considered in this report but not so assigned, particularly certain ones that occurred along the saddles of anticlines. Such a connection of one fire with another later fire presupposes that the actual origin of the second fire took place while the first was active but that it burned slowly in inaccessible territory until some disturbance in the strata, due to the progress of mining, brought it to attention.

Accumulations of hydrogen have very probably been the cause of many gas explosions that have occurred in connection with active fires, which at the time were considered as due to methane.

Anthracite as an Absorbent

Anthracite is known to possess distinctive powers as an absorbent, particularly with respect to carbon dioxide. It is possible that anthracite coal may absorb some of the fumes from fire areas and thus when returns from unsuspected fires join the return air currents they may lack the distinctive odors by which they are usually easily recognized. It is also true that fire fumes and gases cool as they rise through the ground, both by contact and by slight decompression due to change in elevation, with the result that excess moisture is deposited, carrying with it smoke and other small particles and possibly fumes responsible for odors. A return carrying some fire gases is therefore not always recognizable as such either by smell or temperature.

The question of prime importance in this connection is whether carbon monoxide, generated by the combustion of anthracite and regarded as a sure sign of fire, is absorbed by the coal or associated materials after the fire is out and production of CO has ceased. This is known to be the case with bituminous coal, but may not apply in the case of anthracite. Its importance in this particular case lies in the fact that very small amounts of CO have been indicated by a very sensitive detector in areas where fires have been considered to be extinguished for over a year. The indications were not definite, being close to the sensitivity of the instrument, so it remains undetermined whether there really was any CO at these places and, if there was, whether the small amounts found indicate that CO is not absorbed by anthracite coal.

Action of Bacteria on CO

It is reported that a German firm uses a particular type of bacteria to remove CO from manufactured gas, and Bureau of Mines chemists have noted[6] the reduction of CO in such gases where they leak through earth into sewers, apparently a result of bacterial action. This phase of the subject has but recently received attention, but its importance is such that it is hoped that laboratory research, now under way, will quickly determine whether the types of bacteria found in mines have any similar action on CO.

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[6] Jones, G. W., Personal communication.

CONTROL OF MINE FIRES

As has been mentioned before, possibly more than one-half of the total costs of the group of mine fires herein discussed has been occasioned by ineffective measures taken to control and extinguish fires in their initial stages. This not only includes recurrences, where fires were thought to be extinguished but were not, but also fires that were fought by various methods over a period of years and were finally extinguished at high cost or, as respects four, are still active and will entail excessively high costs whether extinguished or allowed to burn.

Methods of controlling and extinguishing fires on steep pitches in broken ground are therefore subjects of paramount importance to mine officials. Judgment as to methods is largely a matter of experience, an intimate knowledge of local conditions, and the application of knowledge concerning the behavior of burning anthracite and associated materials. Regarding the latter, there has been more speculation than actual knowledge, as critical investigations of fire areas, either during the course of the fire or after they have been extinguished, are usually impracticable due to inaccessibility or cost.

While laboratory investigations are yielding theoretical data regarding the combustion of anthracite coal and associated materials that will have direct application to this subject of handling mine fires, its application to specific fires is a question entirely for mine officials thoroughly acquainted with local conditions and with mine fires. All that the author can attempt to do here is to make a few general remarks based on a study of incomplete fire-fighting records and a general knowledge of mining methods, mine gases, and mine ventilation.

Methods of Extinguishing Fires

There are three general methods of extinguishing fires - direct attack on the burning materials, sealing the area containing the fire, and flooding the area including the fire. Practically all fires that are discovered soon after they start can be extinguished by direct attack. Those that require other methods are usually those that have burned undetected for a considerable time in second-mined areas.

Direct Attack

The officials of the group of mines considered have had wide experience in direct attack on mine fires and have been successful in extinguishing all minor fires and about half of their major fires by such methods. Excluding recurrences, there are records of three fires that did permit direct attack, 37 that did not yield to it, and 112 that did. Of the latter, 41 required sufficient effort to be classed as major fires and involved much difficult and dangerous work, as did also the 37 that were not so extinguished and the 22 recurrences.

While direct methods are of major importance as respects the handling of mine fires, they have but slight connection with the present study and will be discussed but briefly.

Small fires have been extinguished easily by water scooped up from the ditch on the gangway in powder boxes and passed in bucket-brigade fashion to the point of use. Chemical extinguishers also have been used freely and, apparently, all mines of this group are liberally supplied with them. For larger fires, bucket brigades usually functioned until water would be supplied by hose. Until compressed-air lines were installed for drilling, pipes and hoses often had to be installed over long distances - 2,000 to 4,000 feet being common - and considerable delays were experienced. Later, air lines were quickly converted to water lines and long delays were eliminated.

Flames of large feeders of gas often have been extinguished by the concussion of a dynamite blast. Small quantities of burning materials usually have been excavated and quenched, or, in the case of surface material, merely spread out to cool. In the case of fires in broken coal stored in breasts, the breasts were drawn usually for some time after the last bit of fire had been drawn and quenched. Where drawing from the chute would be too slow, as in the case of fires high up in breasts in thick coal, an opening was made from a manway and the coal drawn out through it. Occasionally, headings were driven through the broken material and the fire was discovered and quenched by driving spray pipes (short lengths of small-diameter pipe, closed and perforated on the one end, attached to a water hose) into the loose material. In the case of fires in broken coal and rock in pillar mining, the same general procedures were followed: If possible, the burning material was drawn and quenched; otherwise, headings were driven through the mass both to explore it and to provide openings through which water direct from hoses or through spray pipes could be introduced. Various measures were used to assure that all fire was extinguished, such as drawing large excesses of material, running water for hours and days after the fire apparently had been extinguished, and driving headings to surround the suspected area so that regular inspections could be made. In recent years, watchmen have been placed at all fire locations for at least 48 hours and sometimes for weeks and months afterward.

Much of this work was exceedingly difficult, due to working through small openings in high-temperature air, and dangerous, because of fire gases, explosions, and hot steam. Very little use was made of either breathing apparatus or gas masks except in main openings, probably because it is difficult enough to travel in such pitch workings without any encumbrances. In fact, breathing apparatus would be practically out of the question in most of the manways in steep-pitch anthracite workings.

In the records examined there were no references to any special methods of direct attack (such as the flush-tank method of handling steep slope fires, in which a "slug" of water is discharged at intervals from a large tank on surface at the top of the slope) except as regards spray pipes, which apparently have been used widely with success.

Direct attack has failed generally, only in the case of recurrences, where the extent of the fire area was not known or suspected, and in cases of fires that had gained considerable headway in mined-out territory, particularly in thick seams. Here reliance had to be placed mainly in soaking all suspected areas with water, a procedure that often proved ineffective because the water flows mainly in channels and along the bottom or divider slates, and thus may easily by-pass a burning mass and come out cold below, giving a misleading indication that the fire is out.

The records examined say little in regard to ventilation during fire-fighting operations. Most small fires and many larger ones could be fought entirely from the windward side. Occasionally, the normal ventilating currents were short-circuited to cut air off the fire area and provide good ventilation at the points of attack. Occasionally, also, long lines of brattice were used to carry the air forward, particularly on gangways and horizontal fire headings. Wooden box conduits were often used where the broken condition of the ground made line brattice ineffective, or in connection with hand-operated fans. In inclined openings, the heat of the strata driven in would normally produce considerable natural ventilation, as in the case of "fire" slopes driven from the surface.

Although compressed air generally has been available throughout the mines in late years and fan-pipe units with compressed air as motive power have been in use in most mines, apparently fan-pipe installations have been used little to provide good ventilation at points of attack, particularly in "fire" headings, probably because it has been common practice to convert the air lines to water lines, and few places had both air and water lines. The general practice apparently has been for fire fighters to "take it", in short periods of active work where conditions made it necessary.

Provisions for the prompt installation of compressed-air-operated fan-tubing, or injector-tubing, auxiliary ventilation units as required for fighting fires are considered desirable and practically necessary for maximum efficiency. In many sections, this would require the installation of water lines as well as air lines in all gangways and other main openings. Effective injector units require a compressed-air supply of 50 to 100 cubic feet per minute of free air.

Sealing Fire Areas

The records indicate that sealing, with the hope of extinguishing the fire, was tried in at least 24 cases and was successful in but 5. Three of these were in detached areas and but two present the typical conditions under which the method was usually attempted - for fires in pillar-mining workings retreating from a barrier pillar toward an operating opening. In some cases, stoppings were erected only in the gangway and air heading in stump pillars just outside the fire area and pillar mining was then resumed. In other cases, stoppings were placed in the pillar headings several pillars back from the caved ground and pillar mining was continued from a point some distance outby. In the more general case, however, retreat was made to a reservation, slope, or shaft pillar where good seals could be made clear through to surface; or, failing in this, a barrier of solid materials was flushed in through boreholes, as discussed in a later section. Surface breaches were often dynamited if they appeared to be open, and in some cases they were covered with fine culm. However, the sealing of the fire areas was almost uniformly ineffective except to retard the rate of combustion to a minimum. Lack of an effective seal over caved areas at the surface was probably the most important factor in most cases. Passage of air from adjacent seams through joint planes and cracks in the divider rock was possibly a factor in certain instances, and through broken strata over anticlines or saddles in others.

Sealing the area containing the fire, although the most generally accepted and successful method of extinguishing mine fires, has been only moderately successful under conditions prevailing in Western Middle and Southern fields. The steep-pitching parallel seams occur in hard rock strata that have been folded and faulted to a considerable degree; they have been mined to considerable depths without back-filling, and they are breached or caved to the surface along all outcrops. No definite program of leaving reserve or panel pillars has been followed, and opportunities for restricting the area sealed depend entirely on local conditions.

In order that sealing may be effective, the seals must be tight enough virtually to prevent the admission of air to the sealed area, so that the fire will consume the oxygen of the air until it is reduced to a percentage that will not support combustion or rapid oxidation. The atmosphere must then be held in that state until the temperature of the partly burned material falls below the temperature at which it will reignite when the area is opened. In order to reduce the time involved to a reasonable period, therefore, it is desirable to have a fire of sufficient intensity and size in proportion to the area sealed as readily to consume the oxygen of the enclosed area, but not so large that large masses of partly burned material surrounded by ashes or covered by falls will require an indefinite time to cool.

As a method, sealing is generally effective in flat seams under good cover, and in such districts sealing would be generally effective in first-mined operations in solid ground. But fires in such operations are generally fought and extinguished by direct methods, and there are only a few instances of sealing having been resorted to because of the special hazards of direct fighting in each particular case.

Breathing of Sealed Areas

Usually, the greatest difficulty to be overcome in extinguishing fires by sealing is the so-called "breathing" of sealed areas due to changes in barometric pressure. The air in such spaces tends to increase and decrease in volume inversely with the change in barometric pressure, thus alternately putting pressure (decreasing barometric pressure) and suction (increasing barometric pressure) on the seals. If the seals were absolutely tight, the full atmospheric pressure changes (1 inch of mercury pressure equals 13.6 inches of water-gage pressure) would be exerted on them uniformly and in the same direction, and the volume within the enclosure would remain unchanged. Leaks act to reduce the pressure differences on seals by allowing volume changes within the enclosed area. Where the leakage paths are short and connect directly to ventilated areas, the inflow of air to the sealed area may prevent the desired lowering of its oxygen content. However, where the leakage paths constitute unventilated areas, the volume exchanges occur between atmospheres of essentially the same composition and the oxygen content of the sealed area is not affected perceptibly. Often, the changes in volume occur so freely that only the most rapid changes in barometric pressure produce a noticeable effect on the pressure differences on seals.

Natural Ventilation in Sealed and Partly Sealed Areas

Fires or heated masses in inclined workings generate pressure by temperature differences, which will cause air to circulate in the openings present. In the case of a sealed fire area, the recirculation by natural drafts of the atmosphere within the seals tends to maintain a uniform gas mixture, promotes the rapid reduction of the oxygen content, and aids in the more rapid dissipation of heat. In the case of partly sealed areas, natural draft pressures not only cause recirculation within the area but also cause leakage through seals, cracks in the strata, and caved ground, which effects may be reinforced by or be almost wholly due to pressures caused by unequal densities due to differences of chemical composition as between the gases in the enclosed area and the air in surrounding openings.

The many cases in which sealing has been used to retard the extension of fires indicate that the circulations ordinarily are feeble and the oxygen content barely sufficient to maintain combustion. In caved areas on steep pitches, the largest openings probably are in the material nearest the surface, in that alongside barrier and slope pillars, and in that lying against the top slates of the coal seams.

The general tendency of natural drafts is to cause suction on the lower seals of a sealed area and pressure on the upper seals, increasing in intensity with vertical distance from the "neutral zone", or position where the pressure is zero. Under uniform conditions of temperature and air composition, this would be a position just slightly below the vertical center of a perfectly tight enclosed area. Under practical conditions, it is somewhat displaced up or down, but the general statement as regards pressure distribution holds. If normal atmospheres only were involved, natural draft pressures on seals could be estimated as approximately 0.03-inch water gage per 10° F. difference in temperature per 100 feet difference in elevation; but usually the seals are so remote from the fire that temperatures are equalized and the pressure effects noted are largely due to differences in densities between the air-gas mixture within the area and the air without. With 50 percent methane inside of seals, the pressure generated is approximately 0.3 inch water per 100 feet difference in elevation.

Pressures on Seals

Only fragmentary records of pressure on seals were found in the records examined and related to only a few fires, and the few recorded inferences drawn from pressure records were uniformly erroneous. One statement noted is probably representative of the general attitude, of minor officials at least - "just why is a mystery to me." This attitude is easily comprehensible, since the pressures noted are the resultants of so many contending forces that absolute values have little meaning and only relative values and changes in values are significant.

Observed pressures are not only due to variations of barometric pressure, temperatures, air and gas compositions, mechanical and natural drafts, and position and extent of leakage openings, but are also due to the expansion and contraction of the enclosed atmospheres corresponding to changes in condition of the fire and to increased volumes caused by gases (methane) released from the strata. Often, the latter factor predominates and pressures on the seals build up to the point where they have to be released to prevent failure. High pressures, except in the special case of gas outbursts within the affected area, denote tight sealing. However, considerable information can be deduced from the pressures on seals and continuous records (rather than intermittent observations) of pressures on seals in key positions, and of the barometric pressure at a surface station, are desirable matters of record.

Sealing to Retard the Extension of Fires

There is no doubt as to the effectiveness of sealing fire areas to retard the extension of fires, as there are innumerable instances in the records where fires were found to be quiescent and apparently almost extinguished when sealed areas were first opened, but after the areas had been ventilated a few days the fires regained such headway that the areas had to be resealed. In the case of certain fires, this procedure was repeated three and four times, with longer intervals of sealing each time but always with the same final result.

Where the bottom and side seals were good, particularly where the bottom seals were dams on rock tunnels with the area flooded just above their tops, thus insuring tight sealing, fires propagated very slowly, indicating that the amount of air feed from the surface is normally quite small in the case of a deep-seated fire. It has thus been possible to seal a fire off for a number of years without too great a loss of reserves while developing an effective procedure or awaiting a more favorable opportunity for extinguishing it.

Mining Under Sealed Areas

Considering the difficulty and cost of extinguishing large fires in mined-out areas extending to surface and for a mile or more along the strike of the seams, the possibility of mining the coal below a fire area has received considerable attention and at least one intentional trial on a large scale besides many unintentional trials in the case of recurrences. While in some cases a fire has been held at bay, so to speak, for several months until mining to a certain limit has been completed, mining around or under a sealed area has always been hazardous, as all the experiences detailed in the records examined tend to prove.

Theoretically, it would seem possible to develop a procedure that would permit mining to be carried on underneath a fire area with comparative safety, but since the essentials of any safe system would involve a preliminary slushing of the fire area or flooding it to run-off elevation, an unmined chain pillar the full extent of the robbed area, sectional development off rock tunnels, full retreat operations for both first and second mining from property barrier pillars, and possibly hydraulic slushing with waste materials of all openings made in mining, the cost might easily exceed that of an effective method of completely extinguishing the fire by flooding and stripping - the only known effective method for fire areas extending to surface.

Sealing Breaches

At present there is no effective method of sealing breaches. The surface soil is only a few feet deep and of a sandy rocky nature, offering little material that could be flushed easily into the breaches, which are usually a succession of large-diameter cave holes (up to 100 yards wide and 100 feet deep) separated by partly sunken pillars of badly cracked rock and coal and flanked on the top-slate or hanging-wall side by broken strata in which large cracks extend up to a thin layer of surface soil covered with heavy brush or a light stand of second-growth timber.

Slushing deep breaches with fine culm until the excess, over what the openings beneath will take, forms a solid floor over the bottoms of the breaches should form quite effective seals in many cases; but there is no criterion or way of determining their effectiveness, and, in the case of extensive deep workings, the amount of slush required is economically prohibitive. Ground movement over inactive areas is not an important factor. The main requirement for effective sealing would appear to be a material of such nature that a rather thin layer, say a foot or less deep, would form when applied as a spray, or otherwise, and would be virtually impervious to air. In addition to the problem of selecting a low-cost material of the proper characteristics, there is also the problem of its application.

When breaches are slushed full, it is assumed that cracks extending up across the top slates are sealed at their bottoms, and their exact location on the surface, whether concealed or otherwise, is immaterial. But in the case of a surface coating it would be necessary, for effective results, to prepare the surface over a wide strip roughly paralleling the vein, which would mean blasting out small pillars between deep breaches and clearing a wide strip of surface brush and soil so that all cracks of any size could be treated. This denuding process would be so extensive as to require special apparatus, probably hydraulic sluicing apparatus.

Coating materials. - Some thought has been given to the question of coating materials. Water glass, or sodium silicate, was first considered, with the thought in mind that it might be mixed with fine culm to give a colloidal material that would form a thin, flexible, impervious coating. A few laboratory experiments showed that it formed granular mixtures with culm in almost any proportions, and it is therefore not suitable in this combination.

Bentonite, a clay that expands in volume greatly when wet, was also considered. This material is quite expensive, and it is difficult to imagine a procedure under which it could be used sparingly and still be kept wet. Its reduction in volume on drying as as great as its increase when wetted, so it would have to be kept wet.

Consideration of how this might be accomplished brought up the possibility of combining some deliquescent salt with it to abstract the necessary moisture from the air. But many ordinary clays found in mines make fine sealing material in humid atmospheres, and it would seem that a proper material might be formed by mixing a cheap rock salt with a good clay. Apparently, there are no large clay deposits within the district, but plastic clays that should be suitable for this purpose occur within about 40 to 50 miles of the district; and this line of investigation is one that might properly be pursued.

Time Required to Extinguish Fires in Sealed Areas

No one knows just how long it might take to prevent recurrence of a fire in a sealed area. After the fire is extinguished, masses of heated material may remain, and pertinent questions are: What temperature is required to prevent reignition, and how long does it take to cool large masses to that temperature? These questions merit considerable study, and it is possible that the theoretical knowledge required for tentative solutions is available. However, without considering the matter theoretically, it would seem that a sealed area with plenty of voids for circulation of natural draft currents set up by the heat of the fire offers a much better opportunity to reduce the temperature within a short time than a slushed area in which there is little or no void space and in which the heat must be dissipated through poorly conducting materials. However, in the case of the immense areas and thick veins involved in certain of the now active fires, the "short time" referred to above might be measured in years.

Slushing Fire Areas

Slushing a fire area is essentially a method of flooding it, but with solid material instead of water. In these anthracite districts the only material easily and cheaply available and the only one used has been fine culm, or waste coal and rock produced by washing processes in breakers and formerly stored in huge piles all over the district but now largely rewashed for marketable coal or exhausted for slushing except as respects the output of operating breakers. There are no large deposits of sand or clay within a radius of about 50 miles of these fields, and the use of such inert materials for slushing fire areas has not been considered seriously.

While dry slush has at times been dumped directly into mine breaches and other openings, the general procedure has been to pump it into fire areas in suspension with water, usually four parts of water to one part of slush, through 8- to 10-inch cased boreholes 100 to 500 feet deep.

Although occasionally used merely to effect a seal, particularly at inaccessible locations, as by a line of boreholes down the pitch, a ring of holes surrounding a fire area, or single holes intersecting particular openings, the method has been used mainly for directly extinguishing fires either throughout a fire area or in the part above water run-off only. As a method, it has been but indifferently successful. Like sealing, there is no doubt of its effectiveness in retarding the extension of fires, but there is considerable doubt as to the effectiveness of the method for completely extinguishing fires except in the case of small fires and rather simple lay-outs.

The records of this group of mines indicate that it was tried on at least 24 different occasions and that, as far as may now be determined, it was probably successful in 12 instances and probably unsuccessful in 12 instances. However, in most cases the records and the available evidence are not sufficient for accurate decisions.

In the 12 instances considered successful, only six, all of which involved small areas or a simple layout of connected openings, are certain and in some of these, due to lack of provision for rapid draining, the fire areas may actually have been flooded with water. The remaining six may or may not have been extinguished, the probabilities being that they have been. Included in this group are two recently slushed fire areas for which definite evidence may eventually be obtained.

In the group of 12 fires considered not extinguished by slushing, seven were certainly not extinguished and the other five are somewhat doubtful. Flooding of abandoned mines has possibly removed any chance of proving the point as respects three of these, and the other two have been rendered inaccessible by a now active fire generally considered to be a recurrence of them. In both of these fire areas, however, the slushing was largely controlled underground and was apparently sufficiently thorough almost to guarantee filling all openings in the vicinity. In each of these cases, therefore, there is a possibility that the fire was entirely extinguished by slushing, but not before it had been responsible for starting another smouldering fire at a considerable distance.

Slushing to Retard the Extension of Fires

Considered only as a means of retarding the extension of fires, slushing should be a great deal more effective than sealing. In the first place, the water by which the slush is introduced has a great heat capacity, with the result that fires in large areas are quenched and their heat dissipated before the water drains off, leaving the dry slush surrounding and more or less insulating the larger masses of burning material. By filling a large part of the voids in what usually is a partly sealed fire area, flow of air is greatly retarded and inflow by "breathing" likewise. Slushing therefore appears to offer an ideal method of retarding the progress of fires and, where its placement is under sufficient control, offers probably the most effective method of making a seal in broken ground and inaccessible openings.

Flooding Fire Areas

Flooding all or parts of mines to extinguish fires has been the most generally successful method used, even though it must be credited with a large number of failures. Of the 29 attempts shown by the records examined, apparently 12 failed and 17 succeeded, and some of the unsuccessful attempts were remedied by a succeeding attempt. Where the method has been applied properly and the water could get to a level above the fire, it has been successful. Failures have been due principally to two causes - not allowing the area to remain flooded long enough for fires in dead ends to consume the oxygen of the air trapped and compressed in the dead ends, and inability to flood burning areas to the highest levels to which the fire might have penetrated.

In any extensive workings that are flooded, there are bound to be local dead ends in which the rising water will trap air and compress it. Special means can be taken to insure an outlet for the air from large dead-ended sections, but many small ones cannot be handled so, and the only recourse is to allow sufficient time for even a small fire to consume the oxygen and die out. About two months seems to be sufficient for this purpose, and three months is a safe allowance. In the case of most of the early unsuccessful flooding attempts, dewatering was begun the same day the water reached maximum height. In some cases it seems probable that the maximum height was gaged by the known upper extent of the fire area before flooding was done, and did not take into account the possibility that the air and gases forced upward through small openings by the rising waters might have caused a rapid extension of the fire area up the pitch to points above the highest level the water attained.

Use of Dams

In the early days, when the amount of territory covered by a single operation was small or it was necessary to flood but a single lift, dams were not used, as it was customary to flood and subsequently dewater the whole operation, a process that usually required only a few months at the most and involved handling less than 100,000,000 gallons of water. As operations became more extensive, there was not such ready recourse to flooding, as other methods, particularly slushing with culm, appeared to be more advantageous. With recognition of the generally unsuccessful results with this method came a return to the flooding method, limited, however, to the affected section by dams. By this time most of the sections that could be isolated by dams in solid ground were so large that immense quantities of water, from one-half to one billion gallons, were required, and massive dams, costing from $3,000 to $12,000 each, were necessary to guarantee the safety of the rest of the operations while the flooding programs (requiring from 1/2 to 1-1/2 years) were carried out. For the more recent fires, heads on bottom lift dams have ranged from 300 to 750 feet and dams up to 20 feet thick have been used.

The design and construction of such dams is now the most important feature of flooding programs and one that apparently has been handled most competently. Dams are constructed almost entirely in rock tunnels, of brick laid in cement mortar, and usually include a manhole pipe, through which the inside seal is finished first, and a discharge pipe equipped with gun-metal gate valves in duplicate or triplicate. In a few instances in the early days, areas had to be dewatered after partial flooding so that dams could be reinforced, but all recent work has proved to be amply sturdy.

Extinguishing Fires Above Water Level

When the fire is in caved workings that extend to the surface, it is never possible to flood the entire area, as the water will run off at some elevation below the highest elevation occupied by the caved material - possibly several hundred feet lower. Unless precautions are taken to insure that any fire in these areas above water is extinguished by some other method, the cost of flooding may be wasted, as the fire would eventually again extend down the pitch when the area was dewatered. The only certain method of handling these areas above water level has been to dig them out, or remove the material by stripping, and although some commercial coal is thus recovered, the cost is often prohibitive. However, flooding and stripping are now under consideration as means of extinguishing four very large fires that have been burning for years.

In flooding a fire area, the necessity of arranging to put out any fire that might exist above water level would often be largely a question of precaution, particularly in cases of fires that had been burning for years, as it might be assumed that flooding would extinguish the fire where it was most active and that the part above water level would be largely burned out. Sealing the surface with a "coating" seal, as previously discussed, might prove an effective method in such cases, as a short time (a year or less) might be sufficient to dissipate the heat of the fire in the relatively open structure near the surface. It is also possible that a method of using inert gases, as discussed in a following section, might be used with the sealing method to guarantee, by putting the area under pressure with a relatively small supply of inert gas, that all of the area was filled with an inert atmosphere for a definite period. Slushing such areas should be a more effective procedure than slushing the whole fire area, as the assumption could usually be made that the chances that large burning masses might be sealed in by slush would be remote.

Use of Inert Gases for Extinguishing Fires

Since sealing fire areas depends for results on the areas becoming filled with inert gases, the idea of mechanically flooding fire areas with inert gases naturally presents itself. Although a number of attempts have been made to extinguish large fires in anthracite mines by the use of steam and, in at least three instances, carbon dioxide, the results appear to have been practically nil, or at least indeterminate. As far as is known or indicated by the records, no attempts were made to use wither inert gas or steam to subdue any fires in the group under discussion, although the use of CO_2 for this purpose was considered as early as October 1880.

A search of the literature would probably show that the idea of using inert gases has occurred to many at various times. Deputy State mine inspector Joseph J. Walsh discussed a possible installation at a mine inspectors' meeting at Wilkes-Barre in December 1921 and later wrote several papers7/ elaborating on his proposal to discharge cooled flue gases, generated by a special furnace burning fine sizes of anthracite coal, into a partly sealed fire area by means of a small fan. He estimated that a plant having a capacity of 15,000 cubic feet per minute would cost about $20,000, and that the gas would cost somewhat less than 1 cent per 1,000 cubic feet. As far as the author has been able to ascertain, the direct burning of anthracite coal could not be controlled sufficiently to guarantee the required low oxygen and carbon monoxide content of the flue gases.

Since 1930 inert-gas producers have been developed for use in industry for combating explosive-gas hazards, as in purging gas tanks for repair purposes. These are usually mounted on truck trailers, have capacities measured in hundreds of cubic feet per minute, and, with manufactured gas, natural gas, or oil as fuel, are said to be so finely controlled that both the oxygen and carbon monoxide content of the inert gas are practically negligible. The gases are water-cooled and circulated by rotary positive blowers.

A development of this type of portable, closely controlled apparatus rather than a stationary installation without close control, as proposed by Walsh, would seem desirable for trial on anthracite fires. Without special development, fuel oil would have to be used at about 5 to 10 times the approximate cost estimated by Walsh - that is, somewhere between 5 and 10 cents per 1,000 cubic feet. Development of a separate semiportable anthracite-gas producer for gas supply seems an essential requirement for using anthracite coal, which, of course, would be most desirable from the point of view of capacity and cost.

Field of Use

There are two general ways in which inert gas could be used to advantage. One would be to use a limited amount, as in an injector arrangement, to recirculate the fire gases in a sealed area in order to promote the rapid dispersion of heat from burning masses and largely eliminate leakage of air into the area. The other would be the direct discharge of

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7/ Walsh, J. J., Can Mine Fires be Successfully Fought by the Aid of Cooled Boiler Gases?: Coal Age, vol. 21, 1922, pp. 328-9.
Walsh, J. J., Mine Fires and Some Methods of Extinguishing Them: Proc., Coal Min. Inst. Amer., 1923, pp. 75-7.

inert gases into the sealed area under sufficient pressure to cause all leakage to be outward. Neither could be applied with any certainty of success unless the fire area were partly sealed, and neither could be applied indiscriminately.

As respects recirculating fire gases, there would probably be few instances in these fields where intake and return of an affected section would be sufficiently close to form a circuit entirely within the desired area. As respects the second method, economy will probably require that in most instances it would have to be supplemented by other methods in order to reduce the volume requirements. In other words, it would probably be necessary, in the case of extensive fire areas, to fill the majority of the voids in the area by slushing or flooding and, where the area extended to surface, to seal the broken surface so that sufficient pressure could be built up to prevent inleakage due to "breathing" and natural draft pressures. The method is by no means a "cure-all" but might be developed as a useful adjunct, using apparatus in sizes that, though not portable, could be quickly assembled and disassembled.

Its most useful application would appear to be in areas above flood level as a substitute for stripping and might be applied piecemeal in connection with a certain amount of slushing and surface sealing.

Tracing Gas Flow by Odor

In this connection, as well as for the general use of inert gases, it would be desirable to develop a method of applying a distinctive odor to the inert gases to aid in tracing their course and as a matter of general safety. Conditions are so different from those attending other applications of odors that have been made, that actual trials would be required to develop suitable selections.

Proposed Use of "Dry Ice"

"Dry ice", or solid carbon dioxide, has been proposed as a possible source of inert gas for special applications in fighting mine fires. Since the minimum price for this gas would hardly be less than $2 per thousand cubic feet, it is evident that careful consideration would have to be given to possible applications in competition with flooding with water - at an average cost of about $1 per thousand cubic feet - or with flooding with inert gases of combustion - at 10 cents or less per thousand cubic feet. However, the material has definite advantages in regard to portability and in respect to gas density that may easily make economical application to certain special conditions possible and the subject should receive further study.

Proposed Use of Water Fog

The fact that, volume for volume, water has a heat capacity roughly 3,000 times that of inert gases makes it most desirable for extinguishing fires. It is possible, therefore, that fine water fogs now being developed for surface use in combating gasoline and oil fires may not only be used in direct fighting of mine fires but also in the indirect fighting of fires, either alone or in conjunction with inert gases. Experiments along these lines are therefore desirable.

Prevention of Fires

The records examined do not indicate what present practices are with respect to the prevention and detection of fires, but they do show that the hazard and expense of mine fires is largely a matter of detecting them in the incipient stage. A thorough fire-hazard survey of active operations would be required to define present hazards and propose desired changes in practices. Reduction of the hazard and expense due to fires, however, appears to depend on three things - regular inspection of working places within an hour after the workers leave, regular patrol of surface openings and breaches, and reduction in the amount of blasting done under conditions where the result of the blast cannot be inspected. To these might be added a fourth especially applicable to this group of mines - thorough investigation, regardless of cost, of large fire areas to determine definitely that a fire is completely extinguished before resuming mining on the pitch below it.

Restoration of Fire Areas

The mining organizations in these fields appear to be thoroughly competent in reopening and clearing fire areas in order to proceed with production. Parts of large fire areas, however, remain permanently inaccessible except at great difficulty and cost, and few of these have ever been studied to determine what actually occurred. Lack of investigation has at times resulted in recurrence of a fire long afterward.

Sealed fire areas generally have been explored only after the areas have been ventilated to permit explorations in fresh air; and in many cases the areas had to be resealed before much exploring had been done in order to prevent too rapid extension of fires. Preliminary explorations in sealed areas by apparatus crews would appear to be a more effective procedure, and the development of methods of purging gassy fire areas with inert gases would contribute much to the safety of such a procedure; but what is required for maximum safety and effectiveness is a more refined technique for interpreting the results of gas analyses, temperature and pressure records, and other observations at points more or less remote from actual fires.

SUMMARY AND CONCLUSIONS

Records

The records of 177 fires that occurred in a group of steep-pitch anthracite mines, and which included 81 major fires, 22 recurrences, and 74 minor fires, were examined and discussed with mine officials and then compiled and analysed for data on causes, costs, behavior, and control of fires recorded in this report.

Causes

Analyses of the records indicate that about a third of the major fires were caused by explosives, about a fourth each by open lights and open surface fires, and the rest by minor or unknown causes. Explosions or ignitions of methane gas accounted for about one-fifth of the total number of fires and about one-third of those due to open lights and explosives. Most of the major fires so caused resulted from abnormal gas conditions, such as those caused by outbursts, rushes of coal, and large falls.

Fires caused by open lights, long a frequent cause, and by smoking underground (a continuous minor cause), have now passed out of the picture. Electricity has so far been a negligible factor despite its increasing use. There is no evidence in the records of fires due to friction of rock on rock or to spontaneous combustion of the coal or associated materials.

Costs

A detailed estimate indicates that the total cost of fighting underground fires in this group of mines, representing about 12 percent of Pennsylvania anthracite production, would equal at least $10,000,000 in present-day values, equivalent to about 2 cents per ton of coal produced; and four large fire areas remain to be subdued. On the same basis, a rough estimate indicates that the total cost of mine fires in the Pennsylvania anthracite district has probably been more than $50,000,000, equivalent to about 1-1/4 cents per ton of coal produced.

Explosions that caused fires resulted in at least 15 fatalities and 15 serious injuries, and the fires themselves caused at least 18 fatalities and 24 serious injuries besides many cases of minor injury and men overcome for short periods.

Behavior

Fires have burned 15 to 25 years with no evidence easily detectable at remote points surrounding the caved area containing the fire, and have then become ragingly active in a short time after the caved mass was disturbed ny mining on the pitch below. The fact that many fires recurred weeks, months, or even years after they were thought to have been extinguished indicates insufficient knowledge as to the behavior of burning masses in caved areas lying on steep pitches. While known physical and chemical phenomena can account for most of the known and suspected recurrences, a number of factors are involved that are now either unknown or obscure.

The predominant factor in recurrences undoubtedly has been the fact that fire areas have been sealed only partly, as in virtually every case the top was open, either to the surface via caved ground or to unsealed areas via broken strata over anticlines. Natural draft currents could therefore feed air from above to a fire at any depth. Explosions of accumulations of hydrogen gas, distilled from anthracite coal at high temperatures, explain certain "mysterious" recurrences along anticlines, where, although the original fire was extinguished, a new fire appeared without apparent cause in the same vicinity at a later date, even though no evidence of the path of communication was found.

Control

Possibly as much as half of the total cost of the group of mine fires under discussion has been occasioned by ineffective measures to control and extinguish fires in their initial stages.

Fires that had not gained too much headway have, almost always, been extinguished by direct attack and with comparatively little use of breathing apparatus, gas masks, or special ventilation apparatus. Lack of success in direct attack generally has been confined to fires that had gained considerable headway in caved areas in thick seams and to unrecognized recurrences.

Sealing has always been effective in retarding the spread of fires, sometimes to an imperceptible rate, but has generally been used unsuccessfully as a method of extinguishing fires, having been effective in but five of at least twenty-four trials. More effective methods of sealing the surface over broken strata are desirable; a trial of clay and salt mixtures, as used for surfacing minor roads, has therefore been proposed.

Slushing with fine culm has been a very effective method of effecting seals at otherwise inaccessible or impossible locations and of retarding the spread of fires, but has had no certain success as a method of extinguishing fires except for small areas and rather simple layouts. The records indicate that it may have been a success in 12 of 24 trials, but definite evidence is lacking; some of the 12 fires really may have been extinguished by flooding and some may not have been extinguished. Slushing with inert materials offers more promise, but the cost seems to be prohibitive except for small areas.

Flooding apparently is the most generally successful method of extinguishing large fires, with 12 failures and 17 successes recorded and with most of the failures due to two types of evident misapplication - not allowing time for fires in dead ends to consume the oxygen of the air trapped and compressed by the rising water, and inability to flood high enough to cover the fire.

Where the caved areas extend to the surface it is never possible to flood them completely, as the level of run-off may be several hundred feet below the highest outcrop and some other method must be used to supplement flooding for such sections of fire areas. Direct attack by stripping or digging the material out, appears to be the only certain method of handling such areas. It has been applied successfully to many small breach fires but involves almost prohibitive costs for large areas where depths of 200 to 350 feet are required. Effective methods of handling fires in such areas at reasonable costs are urgently desirable.

The use of inert gases for combating fires offers attractive possibilities for handling fire areas above water levels, particularly in conjunction with sealing and slushing designed to minimize the volume requirements and keep operating costs within reasonable limits. Trials of the method could be made with small-capacity oil-burning installations, but for large jobs and continued use it would appear desirable to develop a compact semiportable anthracite gas producer for obtaining large capacity and low cost. Inert gases used for fighting fires should have a distinctive odor, both for safety and for tracing their course.

Since large fires are so difficult and expensive to extinguish, a safe method of mining the coal under fire areas would be very attractive. Whether tried intentionally or unintentionally, this has always been a hazardous procedure and never successful. A thoroughly safe method would probably involve such high costs that its success would always be jeopardized by the desire to "cut corners" in the execution of any prearranged plan.

RECOMMENDATIONS

The following tentative recommendations are offered with regard to steep-pitch anthracite operations, with the knowledge that further study and laboratory research may nullify some and add others. They are purposely couched in general terms, as the study has not progressed to the point where specific recommendations regarding particular situations are justified.

1. Prepare a mine-fire file for study and future reference.
    a. Place a copy of all mine-fire records in a central file.
    b. Complete the records of all major fires as far as is now practicable.
    c. Have a report prepared on all major fires according to a standard form.
    d. Accumulate a reference file of mine-fire data.
2. Endeavor to reduce the number of fires by having a thorough fire-hazard survey made of active operations, with intent to define present hazards and effect required changes in practices.
3. Endeavor to reduce the hazard and expense due to fires.
    a. Institute measures designed to detect fires in their incipient stages, such as
        (1) Regular inspection of all working places within an hour after workers leave.
        (2) Regular patrol of surface openings and breaches.
        (3) Reduction in amount of blasting done under conditions where the result of the blast cannot be inspected.

b. Make more thorough investigations of fire areas to determine whether or not fires are extinguished, with the purpose of preventing unsuspected recurrences.

c. Make a more thorough study of, and disseminate information to minor officials on, the behavior of burning masses of anthracite coal in caved areas on steep pitches, as available from

  (1) Records of past fires.
  (2) Company investigations of active fire areas.
  (3) Laboratory phases of present study by the Bureau of Mines.
  (4) The technical literature.

4. Develop more effective measures for controlling and extinguishing fires that do not yield to direct attack.

  a. Recognize the fact that certain methods, such as sealing and slushing, have been effective only in checking fires rather than extinguishing them, as usually applied; and that flooding and excavation have been the only certainly effective methods used.

  b. Develop methods for use above water run-off level that are as effective as stripping but less costly.

    (1) Flooding with inert gas, formed by controlled burning of anthracite producer gas, is recommended as the method offering the most promise for general utility, particularly as combined with a coating seal of broken surfaces to limit the escape of the gas, and with some form of slushing to reduce the quantity of gas otherwise required

  c. Develop a more refined technique for interpreting results of remote observations, particularly of gas analyses, in terms of the behavior and state of progress of inaccessible fires.